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# Study of two alternative cooling systems of a mold insert used in die casting process of light alloy components

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**Abstract**

A mold insert is an important component of the molds commonly used in die casting processes. Its purpose is to realize particular shapes in castings, like cavities and undercuts. It is also used for improving the cooling system in some critical areas. Each insert has at least one simple cooling channel for controlling the thermal state of the mold and for cooling every *hot spot* efficiently. The severe cyclical thermal conditions, together with the mechanical stresses due at first to the molten metal cast in the shape and then due to the solidified casting, submit the insert to thermomechanical fatigue. The thermomechanical fatigue is the main cause of the cracks observed on insert surfaces after a certain number of cycles, which makes the component unusable and requests its substitution. This circumstance has a negative influence on direct and indirect costs. In this case, the phenomenon has been studied on a mold insert used for realizing an oil drain channel in an aluminum alloy cylinder block made through die casting process. The aim of the present work is to determinate the zones which are mostly subjected to high temperature and high thermal gradients and to design and analyze a more efficient cooling system by using conformal channels on the same insert realized in additive manufacturing.



*Keywords:* Die Casting, Thermomechanical Fatigue, FEM Analysis

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**Nomenclature**

| | |
|---|---|
| $\alpha$ | coefficient of thermal expansion [°C$^{-1}$] |
| b | fatigue strength exponent |
| [C] | thermal capacities matrix |
| c | fatigue ductility exponent |
| $c_p$ | molten metal' specific heat [J/kgK] |
| E | Young modulus [MPa] |
| $\varepsilon_f'$ | fatigue ductility coefficient |
| $\varepsilon_{th}$ | thermal strain |
| $\varepsilon_p$ | plastic strain |
| $\Delta\varepsilon$ | strain range |
| [H] | convective coefficients matrix |
| $h_w$ | convective heat transfer coefficient [W/m$^2$K] |
| [K] | Thermal conductivity matrix |
| m | interface mass of molten metal [kg] |
| $\upsilon$ | Poisson's ratio |
| $\bar{\upsilon}$ | frequency factor |
| $N_f$ | cycles to failure |
| {p} | thermal loads vector |
| q | thermal flux [W/m$^2$] |
| $\sigma_f'$ | fatigue strength coefficient [MPa] |
| $\sigma$ | stress [MPa] |
| {T} | node temperature [°C] |
| $\tau$ | cycle time [s] |
| $T_1$ | cycle lowest temperature [°C] |
| $T_2$ | cycle highest temperature [°C] |
| $T_i$ | coolant inlet temperature [°C] |
| $T_m$ | molten metal temperature [°C] |
| $T_s$ | insert' surface temperature [°C] |
| $T_w$ | wall temperature [°C] |
| W | dissipated energy [J/mm$^3$] |

## 1. Introduction

Roughly half of the aluminum alloys castings which are produced all through the world by the use of gravitational die casting or high pressure die casting (HPDC) are used in different automotive parts and consumer goods. One of the major issues in die casting processes is the durability of the dies and its components; in fact in die casting process, dies are subjected to the high temperatures of the molten aluminum (670 – 710 °C) that flows into the mold at high speed of 30 – 100 m/s and with an injection pressure of 50 – 80 MPa, Jhavar et al. (2013) and Klobčar et al. (2012). A mold insert is an important component of the dies commonly used in die casting processes. Its purpose is to realize particular shapes in castings, like cavities and undercuts. It is also used for improving the cooling system in some critical areas. Each insert has at least one simple cooling channel for controlling the thermal state of the mold and for cooling every *hot spot* efficiently. Die casting dies are subjected to various thermal and mechanical loads. Generally, heat cracking, die soldering and erosion are some of the most relevant phenomena that shorten dies lifetimes, Tentardini et al. (2008). In particular, the severe cyclical thermal conditions, together with the mechanical stresses due firstly to the molten metal cast in the shape and then due to the solidified casting, submit the insert to thermomechanical fatigue. The thermomechanical fatigue is the main cause of the cracks observed on inserts' surfaces after a certain number of cycles, which makes the component unusable and requests its substitution. This circumstance has a negative influence on direct and indirect costs. There have been several studies on life prediction of die casting dies, for example Srivastava et al. (2004) presented a methodology to predict thermal fatigue cracking in die casting dies using a FEM software; they showed that as temperature and thermal gradient increased, the number of cycles to failure decreased considerably. The FEM software can simulate thermomechanical problems very well, Astarita et al. (2013), Sepe et al. (2014). In this paper, the phenomenon has been approached through finite element analysis on a mold insert used for realizing an oil drain channel in an aluminum alloy cylinder block made through HPDC. The aim is to determinate the zones which are mostly subjected to high temperature and high thermal gradients and to design and analyze a more efficient cooling system by using conformal channels realized in additive manufacturing on the same insert.

Die casting is substantially a thermal process; in fact, great heat energy is required to superheat the casting alloy into the liquid state with the desired viscosity. The way that allows to monitor the heat energy at each point of the process is to measure and control the temperature. In this kind of process, the casting dies together with its inserts work as a heat exchanger, so they are subjected to severe thermal gradients, in particular the core is colder than the surface that is directly exposed to the molten metal flow. Thermal gradients generate stresses and deformations cyclically that lead to a phenomenon known as thermomechanical fatigue which involves the nucleation and the growth of cracks on the surfaces known as “heat checks”, Srivastava et al. (2004). Figure 1 shows an example of such type of cracking.

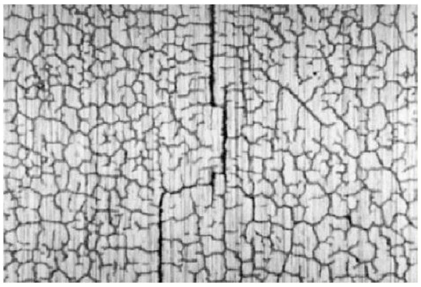

Fig. 1. Example of *heat checks*, Srivastava et al. (2004).

Macroscopically, the cracking initiates due to the strong thermal shock experienced by the die surface when it is rapidly heated to 700 °C and then quenched to 200 °C by the lubricant spray. During heating the thermal gradients put the die steel surface in compression while during cooling put them in tension.

Fatigue can be described by the well-known Coffin-Manson equation (1) that indicates that the number of reversals to nucleate cracks vary exponentially with the plastic strain amplitude which is related with mechanical properties of material.

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c \qquad (1)$$

The thermal strain is evaluated by the following equation:

$$\varepsilon_{th} = \alpha(T_2 - T_1) = \alpha\Delta T \qquad (2)$$

where $\alpha$ is the coefficient of thermal expansion, $T_1$ and $T_2$ are the lowest and the highest temperature of the cycle respectively.

During the first phase of the casting cycle, the surface of the insert is at higher temperature than the core one, so its expansion is constrained by the colder elements in the core and it will be subjected to compressive stresses given by equation:

$$\sigma(T) = E(T)\left[\varepsilon_{tot}(T) - \alpha(T)\Delta T\right] \tag{3}$$

Figure 2 shows stresses vs time during one whole cycle: compressive stresses grow during the heating phase while the material remains in the elastic field until the compressive yield strength is reached; here it can be defined a critical value for temperature $T_C$ which defines the transition between the elastic and the plastic fields.

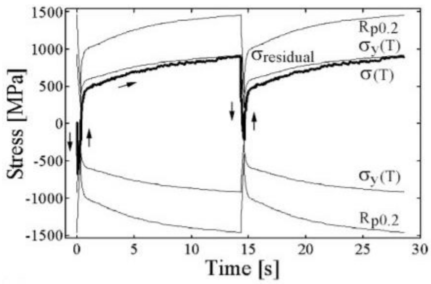


Fig. 2. Cyclical stresses, Persson (2003)

Starting from this point, there is accumulation of plastic deformation up to the maximum temperature of the cycle, that can be evaluated by the following equation:

$$\varepsilon_p = \varepsilon(T_2) - \frac{\sigma_Y(T_C)}{E(T_C)} \tag{4}$$

The plastic strain could be also used to predict the number of reversals to failure. According to Sissa et al. (2014), an energetic criterion should be employed, in fact, the fatigue life of materials is strongly influenced by the dissipated energy per cycle defined by (5) as suggested by equation (6) in which C and β are material constants:

$$\Delta W = \int_t^{t+\Delta t} \sigma d\varepsilon_p \tag{5}$$

$$\Delta W N_f^{\beta} = C \tag{6}$$

Definitely, the thermomechanical fatigue resistance depends on the characteristics of the thermal cycle (maximum cycle temperature, pre-heating dies temperature, cooling down velocity) and it is also strongly influenced by material properties. In particular, a low value of the thermal expansion coefficient would be preferable in order to minimize thermal strains, while a high value of the thermal conductivity allows to obtain a more uniform temperature distribution between the surface and the core, Lu et al. (2019). The insert cooling system also plays a crucial role, thanks to which is easier to get the control over temperature.

In the present work, firstly, in order to get the temperature field of the insert, a casting cycle has been simulated through a thermal finite element analysis model, then the resultant thermal field has been applied as load in a subsequent structural analysis, as show in Figure 3. In view of the results, a more efficient conformal cooling system has been designed and then compared.

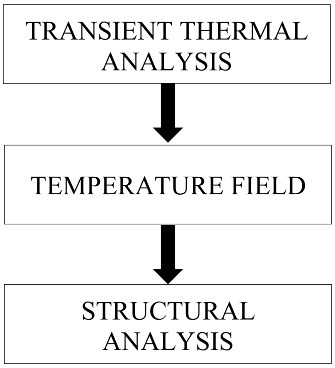


Fig. 3. Analysis flow chart.

## 2. Preparation of the thermal model

In this phase the aim is to extract the temperature field of the insert when specific boundary conditions are applied. In this work it has been assumed that the main cause of heating and cooling phenomena which involves the insert, is the fluctuating temperature of the molten metal during its solidification. For this reason, a time dependent thermal cycle has been defined in order to simulate this temperature variation. In the first transient thermal analysis an initial temperature of the insert has been considered equal to the pre-heating temperature of the mold which is 200°C, while the molten aluminum alloy is casted at 700°C. Because of the molten metal, the insert is subjected to a time variable heat flux, obtained with a previous fluid dynamics simulation and expressed by the polynomial (7):

$$q = 3152,8 - 188,8t + 9,5t^2 - 0,21t^3 + 0,0015t^4 \tag{7}$$

The extension of the heat exchange surface is 10.603,5 $mm^2$, the cycle time is 45 seconds. During the entire cycle the insert is cooled down by demineralized water at 25 °C. The mass flow rate of the coolant fluid is equal to $\dot{m} = 0{,}278\ l/s$. The amount of heat removed by water is given by equation (8):

$$Q = h_w \left(T_w - T_i\right) \tag{8}$$

The convective heat transfer coefficient has been calculated through the Dittus-Boelter equation (9):

$$h_w = \frac{k_w}{D} Nu \tag{9}$$

where $k_w = 0{,}60\ W/mK$ is the water thermal conductivity, $D = 3\ mm$ is the diameter of the cooling channel and *Nu* is the Nusselt number, calculated as follows:

$$Nu = 0,023 Re^{0,8} Pr^{0,4} \tag{10}$$

Specific heat for water is $c_p = 4180\ J/kgK$, dynamic viscosity is $\mu = 8{,}94 * 10^{-4}\ Pa * s$, $\rho = 997\ kg/m^3$ is water density and $v = 1{,}2\ m/s$ is its velocity through the channel, so Prandtl and Reynolds numbers can be calculated as follows:

$$\mathrm{Pr} = \frac{c_p \mu}{k_w} = 6,23 \tag{11}$$

$$\mathrm{Re} = \frac{\rho v D}{\mu} = 4014,8 \tag{12}$$

Nusselt number becomes equal to 35 and $h_w = 7\ kW/m^2K$.

Analytically, the evolution of the temperature on insert surface is given by integration for variable separation of the amount of heat transferred from the molten metal, Matisková et al. (2013). In the time *dt*, the amount of heat transferred on insert surface is:

$$dQ = hS * \left(T_m - T_s\right) dt = -mc_p dt \tag{13}$$

So

$$Q = \int_{T_s}^{T_m} \frac{d(T_m - T_s)}{T_m - T_s} = -\int_0^t \frac{hS}{mc_p} dt \tag{14}$$

$$T_s(t) = T_m \left( 1 - e^{-\frac{hS}{mc_p} t} \right) \tag{15}$$

A schematic representation of this phase is shown in Figure 4.

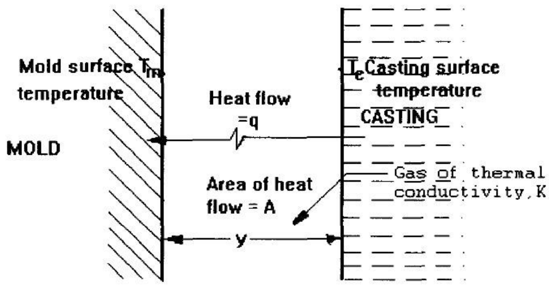


Fig. 4. Schematization of heat transfer mechanism, Krishnan and Sharma (1996).

The conductive heat exchange phenomenon, which takes place into a solid body when a temperature gradient is present, is modelled by Fourier's law:

$$Q = -kA\nabla T \tag{16}$$

To determine the features required to the cooling system, considering for an aluminum-silicon alloy casting an extraction temperature $T_g = 250\ °C$ , $T_m = 700\ °C$, a mass $m = 20\ kg$ , a latent heat of solidification

$l = 385{,}2\ kJ/kg$ and a specific heat $c_s = 0{,}962\ kJ/kgK$, it is possible to estimate the thermal work of the dies by calculating the heat transferred during each cycle as follows:

$$Q = m\left[l + c_s\left(T_m - T_g\right)\right] \tag{17}$$

The amount of heat transferred to dies in a single cycle is equal to $1{,}63 \cdot 10^4\ kJ$.

Analyses have been performed with the finite element method. The finite element matrix equation that describes the transient thermal analysis is:

$$\{p\} = [C]\{\dot{T}\} + ([K] + [H])\{T\} \tag{18}$$

where the thermal conduction matrix [K] is obtained by volume integration of the model element temperatures vector.

The steel used for the simulation is a CrMoV alloyed hot work tool steel Wr. Nr. 1.2343, this steel is one of the most common materials used for producing dies for HPDC. During aluminum die casting process this steel operates at temperatures around secondary hardening or even higher, under such operating conditions almost all steels present a general softening trend. The undesired softening also aggravates material yield strength, Bergström and Rézai-Aria (2006). Thermal and mechanical properties of the hot work tool steel are listed in table 1.

Table 1. Thermal and mechanical properties of 1.2343 hot work tool steel.

| Temperature | 20°C | 400°C | 500°C | 600°C |
|---|---|---|---|---|
| Elastic longitudinal modulus [GPa] | 215 | 183 | 176 | 165 |
| Elastic shear modulus [GPa] | 82 | 70,2 | 68 | 63 |
| Ultimate tensile strength [MPa] | 1550 | 1300 | 1100 | 800 |
| Yield strength [MPa] | 1450 | 1100 | 900 | 600 |
| Thermal expansion coefficient [$°C^{-1}$] | $12{,}0*10^{-6}$ | $12{,}5*10^{-6}$ | $12{,}9*10^{-6}$ | $13{,}0*10^{-6}$ |
| Thermal conductivity [W/mK] | 25 | 27,2 | 28,5 | 29,3 |
| Density [$kg/dm^3$] | 7,80 | 7,70 | 7,64 | 7,60 |
| Specific heat [J/kgK] | 460 | 500 | 550 | 590 |

Figure 5 shows the model prepared for the analysis that covers a typical die-casting cycle of 45 seconds.

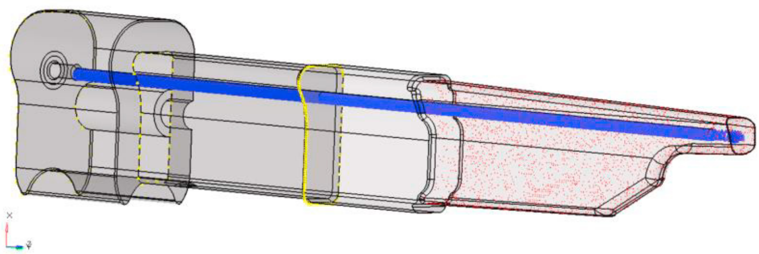

Fig. 5. CAD Model.

## 3. Results of the thermal analysis

According to Abdulhadi et al. (2016), the existence of a noticeable thermal gradient between the surface and the core is one of the main causes of rupture under thermomechanical fatigue. Figure 6 shows the result of thermal analysis on a section plane that has coordinates (0,100,0). Eight points have been underlined and their temperatures have been plotted over time as shown in Figure 7.

It can be seen that temperature reaches its maximum in every point nine seconds after the molten metal has being poured into the mold, then it decreases more rapidly around the points that have been set externally even if they keep the highest temperatures at the end of the thermal cycle because of their distance from the cooling channel. Points 3 and 4 have been constrained at T=25°C, so their temperature remains constant during the whole cycle.

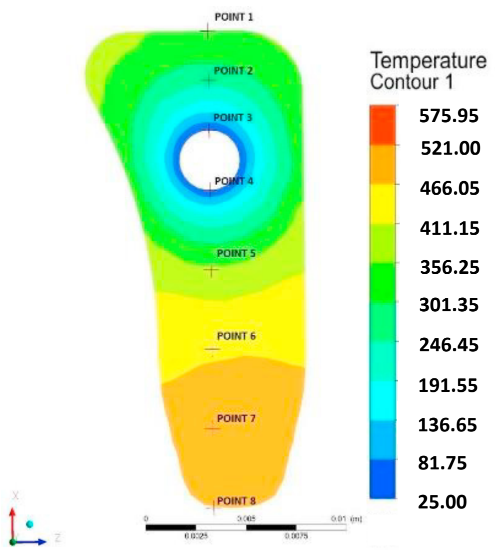


Fig. 6. Temperature in the core of the insert [°C].

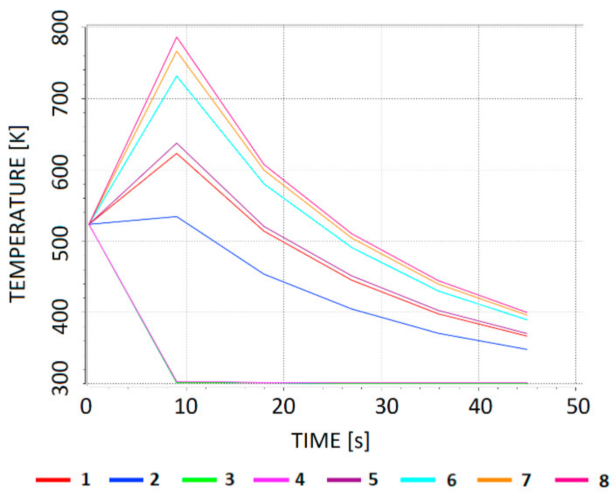


Fig. 7. Temperature plot of eight points on insert' section.

Moreover, there are thermal gradients also between the area of the insert that is directly exposed to the flux of the coolant that flows in the channel and the rest of the insert. It can be concluded that this part of the insert is hotter due to the inefficient cooling system. This result is represented in Figure 8 in different instants of the thermal cycle.

Thermal gradients observed in this analysis may force contiguous elements to hire different lengths, as already discussed, but it is not possible due to the displacements congruence, so this origins stresses in that area that could be tensile or compressive stresses based on the sign of the thermal gradient. In particular, the area near the cooling channel cools down faster, so it tends to contract more but it is constrained by adjacent zone at higher temperature, thus tensile stresses will appear on the surface in that zone. These tensile stresses act on the component cyclically at each new casting.

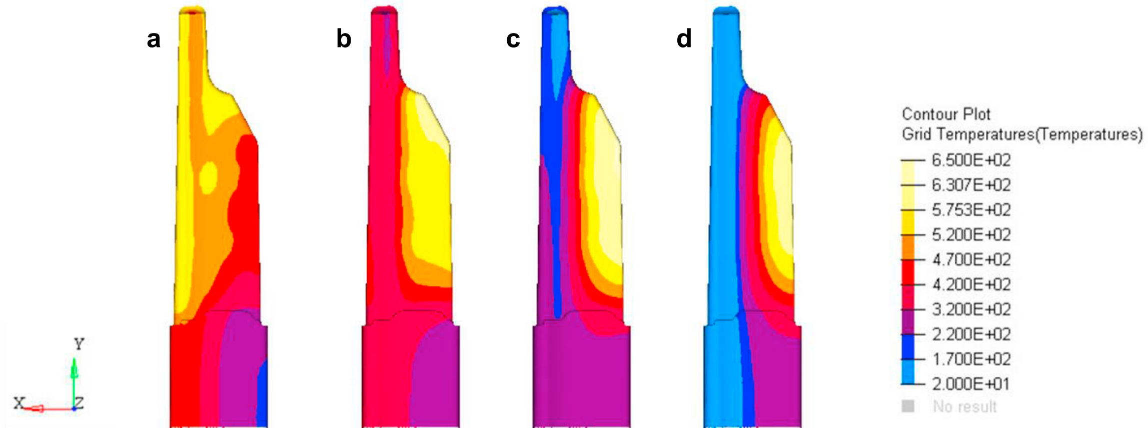


Fig. 8. Thermal fields [°C] at (a) 15 s; (b) 25 s; (c) 35 s; (d) 45 s.

## 4. Preparation and results of the structural analysis

The time variable temperature field has been exported and applied as a load in the structural analysis. Before running the analysis, the model has been constrained with fixed joints in order to simulate the assembly in the mold and the bond effect of the alloy during the solidification.

The results of the structural analysis underline a stress intensification in the area where the thermal gradient was higher, as shown in Figure 9. At the end of the cycle the maximum von Mises equivalent stress is about 370 MPa.

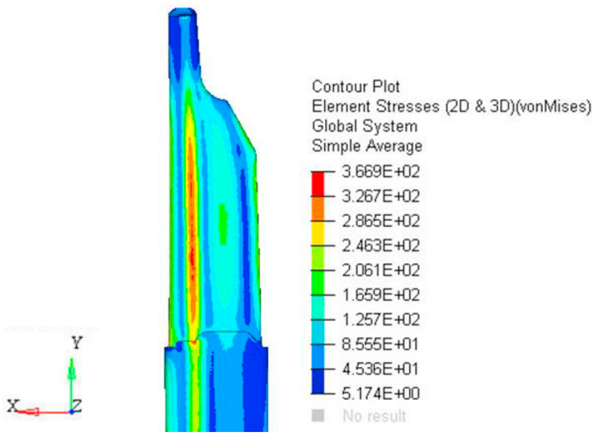


Fig. 9. Von Mises stresses on the insert at 45 seconds [MPa].

There have also been detected large areas where plasticity occurs, so this result together with the high temperatures, can be considered as an indicator of low-cycle life phenomena. The analysis of the dissipated energy showed that the highest amounts of energy are dissipated in the area where thermal gradients are maximum. The highest value observed is $W = 4{,}81 \cdot 10^{-1}\, J/mm^3$.

The variable amplitude stresses spectrum obtained in this analysis can be used for fatigue calculations; in this case it should be a case of multiaxial fatigue because the six independent components of the Cartesian stress tensor are time-variable with different laws as shown in the following Figure 10.

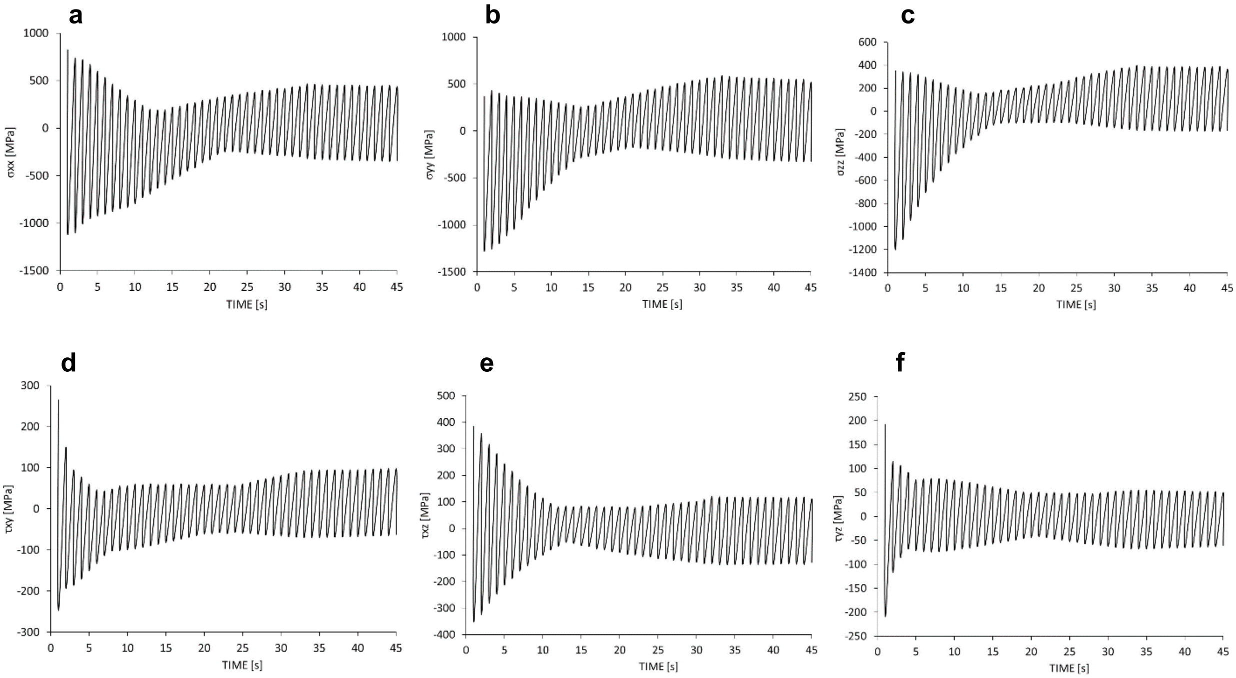


Fig. 10. Stresses' spectrum: (a) $\sigma_{xx}$; (b) $\sigma_{yy}$; (c) $\sigma_{zz}$; (d) $\tau_{xy}$; (e) $\tau_{xz}$; (f) $\tau_{yz}$.

## 5. Conformal cooling channels

The most commonly used technology for the realization of the inserts cooling systems is the traditional drilling. This kind of machining allows to manufacture only cylindrical and straight channels thus, as seen, it leads to a nonhomogeneous heat transfer that causes the alteration of the process, Phull et al. (2018). With the additive technology known as *Select Laser Melting (SLM),* is possible to realize every kind of complex geometries because metal powders are sintered by a laser beam that follows a path imposed by a CNC machine reading an imported CAD of the component, Abbès et al. (2019).

Dang and Park (2011) proposed the design optimization process in order to obtain an optimal cooling channels' configuration and target mold temperature. Kuo and Xu (2018) highly recommend the series conformal cooling channel as a solution to enhance the productivity of a new product in the injection molding process.

A new insert cooling system has been designed in the order to improve its efficiency. Figure 11 shows the new conformal cooling channels for a more uniform temperature distribution.

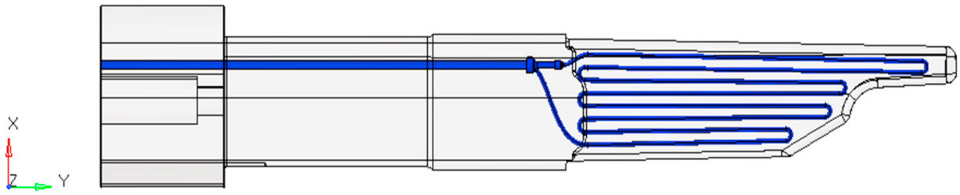


Fig. 11. Insert with conformal cooling system.

One limit of the technology is its non-applicability to a wide range of materials, but it is limited to the metals that are available in powder. One of these is the *maraging* steel Wr. Nr. 1.2709 whose properties are listed in Table 2.

Table 2. Thermal and mechanical properties of 1.2709 maraging steel.

| Temperature | 20°C | 500°C |
|---|---|---|
| Elastic longitudinal modulus [GPA] | 180 | 169 |
| Ultimate tensile strength [MPa] | 2050 | 1860 |
| Yield strength [MPa] | 1900 | 1700 |
| Thermal conductivity [W/mK] | 19 | 21 |
| Density [kg/dm$^3$] | 8,0 | 7,8 |
| Specific heat [J/kgK] | 430 | 460 |

The aim is to obtain a more uniform thermal field in fact, this would lead to:

- increase insert life;
- reduce the strains that caused distortions in castings;
- reduce the cycle time, Shayfull et al. (2014).

A transient thermal analysis on the new insert has been done with the purpose of comparing the results obtained in the two cases. The analysis has been conducted under the same boundary conditions. Figure 12 shows the comparison of the thermal distributions between the insert with the traditional cooling system and the one with the conformal channels at 25 seconds. It is clear that, in the second one the thermal field is quite uniform all over the surface so thermal gradients are practically absent and the highest temperature reached is lower.

Moreover, the analysis shows that the average temperature of the insert is almost equal to the initial one after only 30 seconds (Figure 13): it suggests that an optimal thermal control could reduce the cycle time with the increase of the production rate. Sachs et al. (1997) tested tooling inserts with a variety of patterns of conformal cooling showing a reduction in cycle time up to 15% and a reduction in the part distortion up to 37%.

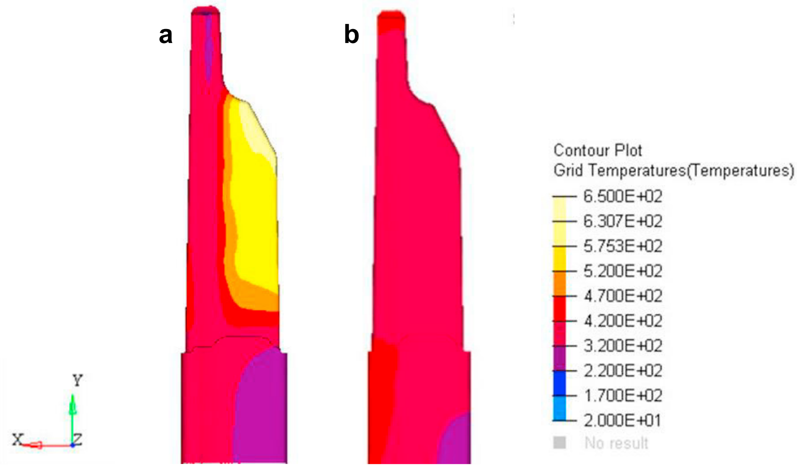


Fig. 12. Comparison of temperature field [°C], after 25 seconds, between (a) traditional cooling channel and (b) conformal cooling channels.

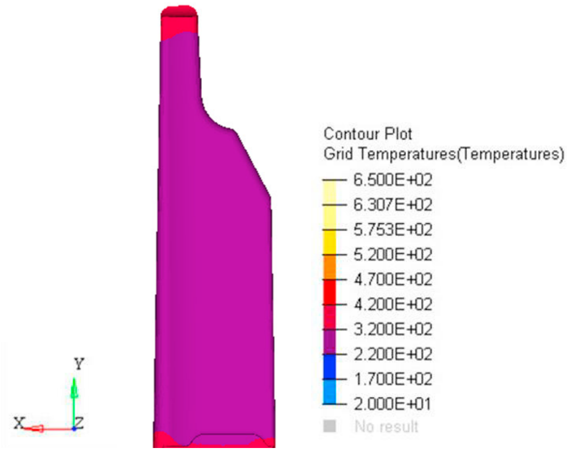


Fig. 13. Temperature field [°C] after 30 seconds.

Figure 14 represents the temperature field in a section plane that has the same coordinates as the one showed in Figure 6. It can be seen that with conformal cooling channels the average temperature in the core of the insert is lower than the one calculated with the traditional cooling system and, at the same time, is more uniform without the presence of large high temperatures areas as the ones observed before in the lower filleted zone of the insert.

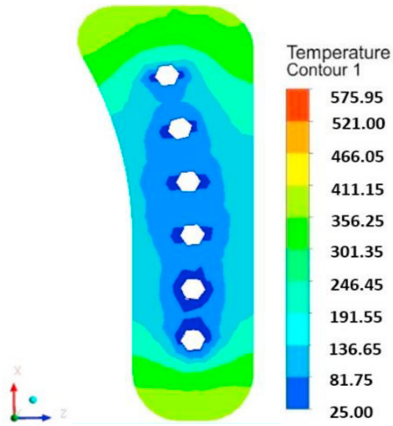


Fig. 14. Thermal field in the core of the insert [°C].

This result is also confirmed by the subsequent structural analysis; despite the equivalent von Mises stresses are of the same magnitude, there is a lack of stress intensification as shown in Figure 15.

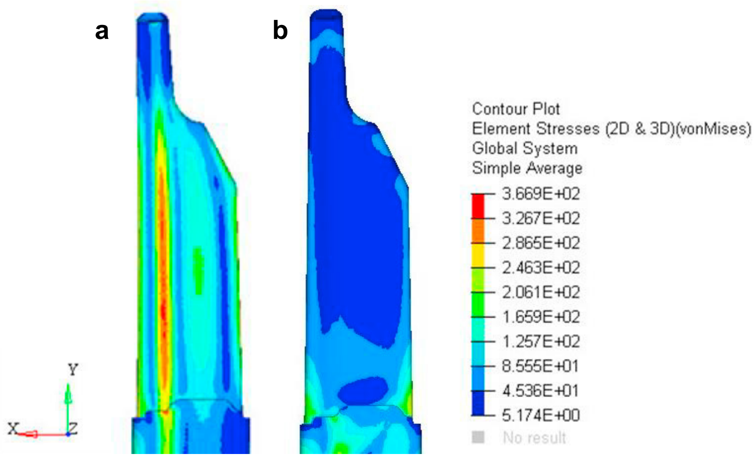


Fig. 15. Comparison of the von Mises stresses [MPa] between (a) traditional cooling channel and (b) conformal cooling channels.

## 6. Conclusions

Injection molding is one of the frequently used processing technologies to manufacture automotive parts with high productivity. In order to improve productivity and part quality, optimal thermal management of injection mold and its components is an essential step in the mold design. It has been found that a conformal cooling system is a valid solution to uniformly cool a mold insert while reducing the effects of thermomechanical fatigue. Die casting processes are easily affected by it because of their typical high temperatures that evolve in few seconds.

In this paper we presented two finite element simulations in order to analyze and compare the temperature and the stress fields obtained on the insert with two different cooling systems and find out the better system that could limit the frequent substitutions of the inserts.

In conclusion, for what concerns the cooling systems, it is clear that conformal cooling channels bring a series of improvements in terms of reduction of mechanical and thermal stresses and cycle time.

There are advantages for both the product and the process; on a hand less defects on castings, on the other hand less thermomechanical stresses on the inserts with the improvement of the insert duration. In fact, the optimal thermal conditioning prevents degradation of the steel microstructure caused by prolonged exposure to high temperature.

At last, the fast cooling observed with the conformal cooling channels allows to increase the productivity.
In further developments, the energetic fatigue criterion expressed by equation (6) will be used to predict and compare the duration of the two components.

## References


Abbès, B., Abbès, F., Abdessalam, H., Upganlawar, A. 2019. Finite element cooling simulations of conformal cooling hybrid injection molding tools manufactured by selective laser melting. The International Journal of Advanced Manufacturing Technology 103, 2515–2522.

Abdulhadi, H.A., Aqida, S.N., Ishak, M., Mohammed, G.R., 2016. Thermal Fatigue of Die-Casting Dies: An Overview. MATEC Web of Conferences 74. 00032.

Astarita, A., Armentani, E., Ceretti, E., Giorleo, L., Mastrilli, P., Paradiso, V., Scherillo, F., Squillace, A., Velotti, C., 2013. Hot Stretch Forming of a titanium alloy component for aeronautic: mechanical and modeling, Key Engineering Materials 554-557, 647-656.

Bergström, J., Rézai-Aria, F., 2006. High temperature fatigue of tool steels. In: Rosso M, Actis Grande M, Ugues D, editors. Tool, proceedings of 7th international tooling conference, Torino.

Dang, X.P., Park, H.S., 2011. Design of U-shape milled groove conformal cooling channels for plastic injection mold. International Journal of Precision Engineering and Manufacturing 12, 73–84.

Jhavar, S., Paul, C.P., Jain, N.K., 2013. Causes of failure and repairing options for dies and molds: A review. Engineering Failure Analysis 34, 519-535.

Klobčar, D., Kosec, L., Kosec, B., Tušek, J., 2012. Thermo fatigue cracking of die casting dies. Engineering Failure Analysis 20, 43-53.

Krishnan, M., Sharma, D.G.R., 1996. Determination of the interfacial heat transfer coefficient h in unidirectional heat flow by Beck's non linear estimation procedure. International Communications in Heat Mass Transfer 23, 203-214.

Kuo, C.C., Xu, W.C., 2018. Effects of different cooling channels on the cooling efficiency in the wax injection molding process. The International Journal of Advanced Manufacturing Technology 98, 887–895.

Lu, Y., Ripplinger, K., Huang, X., Mao, Y., Detwiler, D., Luo, A., 2019. A new fatigue life model for thermally-induced cracking in H13 steel dies for die casting. Journal of Materials Processing Tech 271, 444–454.

Matisková, D., Gašpar, Š., Mura, L., 2013. Thermal Factors of Die Casting and Their Impact on the Service Life of Moulds and the Quality of Castings. Acta Polytechnica Hungarica 10, 65-78.

Persson, A., 2003. On Tool Failure in Die Casting. Acta Universitatis Upsaliensis.

Phull, G.S., Kumar, S., Walia, R.S., 2018. Conformal cooling for molds produced by additive manufacturing: a review. International Journal of Mechanical Engineering and Technology 9, 1162–1172.

Sachs, E., Allen, S., Guo, H., Banos, J., Cima, M., Serdy, J., Brancazio, D., 1997. Progress on Tooling by 3D Printing; Conformal Cooling, Dimensional Control, Surface Finish and Hardness. International Solid Freeform Fabrication Symposium, 115-124.

Sepe, R., Pozzi, A., Armentani, E., 2014. Finite-element simulation of temperature fields and residual stresses in butt welded joints and comparison with experimental measurements, ASME 12th Biennial Conference on Engineering Systems Design and Analysis 1, 1-6.

Shayfull, Z., Sharif, S., Ghazali, M.F., Mohd Saad, R., 2014. Potential of Conformal Cooling Channels in Rapid Heat Cycle Molding: A Review. Advances in Polymer Technology 33, 21381.

Sissa, S., Giacopini, M., Rosi, R., 2014. Low-Cycle Thermal Fatigue and High-Cycle Vibration Fatigue Life Estimation of a Diesel Engine Exhaust Manifold. Procedia Engineering 74, 105-112.

Srivastava, A., Joshi, V., Shivpuri, R., 2004. Computer modeling and prediction of thermal fatigue cracking in die casting tooling. Wear 256, 38-43.

Tentardini, E.K., Kunrath, A.O., Aguzzoli, C., Castro, M., Moore, J.J., Baumvol, I.J.R., 2008. Soldering mechanisms in materials and coatings for aluminum die casting. Surface and Coating Technology 202, 3764-3771.